STAR FORMATION AND CHEMICAL EVOLUTION IN DAMPED LYα CLOUDS

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ABSTRACT

Using the redshift evolution of the neutral hydrogen density, as inferred from observations of damped Lyα clouds, we calculate the evolution of star formation rates and elemental abundances in the universe. For most observables our calculations are in rough agreement with previous results based on the instantaneous re-cycling approximation (IRA). However, for the key metallicity tracer Zn, we find a better match to the observed abundance at high redshift than that given by the constant-yield IRA model. We investigate whether the redshift evolution of deuterium, depressions in the diffuse extragalactic gamma-ray background, and measurement of the MeV neutrino background may help determine if observational bias due to dust obscuration is important. We also indicate how the importance of dust on the calculations can be significantly reduced if correlations of the HI column density with metallicity are present. The possibilities for measuring q_o with observations of elemental abundances in damped Lyα systems are discussed.

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1. INTRODUCTION

It is widely believed that the damped Lyα systems contain the vast majority of the cool neutral gas at high redshift. Recent observational studies which attempt to determine the redshift evolution of this gas (Pettini *et al.* 1994; Lanzetta *et al.* 1995; Storrie-Lombardi *et al.* 1995), open up the possibility of seriously exploring cosmic chemical evolution in the early universe. This is especially true if the cool gas can be considered to be a closed box system, since this allows for the most direct inference of the universal star formation rate (SFR). Such a direct knowledge of the SFR greatly reduces the input uncertainties to the chemical evolution equations. Based on their observations, and the use of instantaneous re-cycling approximation (IRA) calculations, Lanzetta *et al.* (1995) give a series of compelling arguments which argue in favor of the closed box models, and against inflow/outflow models. In the calculations reported here we will assume that the chemical evolution equations are indeed accurately described by closed box models.

The reasons for the present study are three-fold. First, we wish to carry out chemical evolution calculations which do not utilize the IRA. In doing so we wish to assess the reliability of previous calculations which make this assumption. Secondly, we wish to explore the possibilities of testing cosmology with future observations of elemental abundances in damped Lyα systems. Third, we wish to explore the influence on the chemical evolution of observational bias introduced by dust obscuration of background quasars, and to determine possible tests for such bias. Recently, Pei and Fall (1995) have argued that such dust contamination could in fact strongly influence the predicted chemical evolution.

2. CHEMICAL EVOLUTION

The cosmological gas density $\Omega_g(z)$ is defined as the comoving gas mass density at a redshift z in units of the present critical density ρ_c. It is given by

$$\Omega_g(z) = \frac{H_o \mu m_h}{c \rho_c} \int_{N_{min}}^{N_{max}} f(N,z) N dN \tag{1}$$

where c is light speed, H_o is Hubble's constant, μ is the mean particle mass per m_h (the mass of an H atom), N is the column density of HI, and $f(N,z)dNdX$ is the number of absorption systems per line of sight with column density in the interval N to $N + dN$ and "absorption distance" in the interval X to $X + dX$. The coordinate X is defined through

$$X(z) = \int_0^z (1+z)(1+2q_o z)^{-1/2} dz \tag{2}$$

where q_o is the de-acceleration parameter. We assume any molecular abundances to be negligible and take $\Omega_g(z) = 1.3\Omega_{\rm HI}(z)$.

Assuming zero cosmological constant and neglecting radiation, the relation between redshift z and time t can be written

$$\frac{dt}{dz} = -\frac{H_o^{-1}}{1+z}\left[\Omega_m(1+z)^3 - \Omega_k(1+z)^2\right]^{-1/2} \tag{3}$$

where

$$\Omega_m = (\rho/\rho_c)_o = 8\pi G\rho/3H_o^2; \quad \Omega_k = Kc^2/H_o^2 \ \ (K = \pm 1, 0) \quad .$$

From the above relations the redshift evolution of the cosmic gas in a closed box model is described by the following equation

$$\frac{d\Omega_g}{dz} = \left\{ \int_{m(z)}^{m_{up}} (m - m_r)\Psi(z_m^f)\Phi(m)dm - \Psi(z) \right\}\frac{dt}{dz} \quad . \tag{4}$$

Here z_m^f is the formation redshift at which a star of mass m is returning gas back to the interstellar medium at the current redshift z, Ψ is the SFR, and Φ is the initial mass function (IMF). The lower limit of integration $m(z)$ is the minimum stellar mass which can be returning gas to the interstellar medium at redshift z. For the remnant mass function m_r, the relations of Iben and Tutukov (1984) are adopted; and for the stellar lifetimes the

relations of Scalo (1986) are adopted. Note that a small correction due to the presence of type Ia supernovae is actually added to eq. (4) in our calculation (see discussion below); for the evolution of the gas this contribution is unimportant and for clarity it is not explicitly shown above. We assume a power law for the IMF viz. $\Phi(m) \propto m^{-(1+x)}$, ($x$ is termed the slope of the IMF) and it is normalized through the relation

$$\int_{m_{low}}^{m_{up}} m\Phi(m)dm = 1 \quad .\tag{5}$$

The upper and lower mass limits are taken to be $m_{up} = 40M_\odot$ and $m_{low} = 0.08M_\odot$, respectively. In this notation $x = 1.35$ corresponds to the Salpeter IMF.

We choose to parameterize the observed and dust-corrected evolution of $\Omega_{\mathrm{HI}}(z)$ through the functional forms given by Pei and Fall (1995). The observational data is then described through

$$\Omega_{\mathrm{HI}}(z) = \frac{\Omega_{\mathrm{HI}}(\infty)\exp(\alpha z)}{\exp(\alpha z) + \exp(\alpha z_b)}\tag{6}$$

where α and z_b are two of the available fitting parameters (dependent on the adopted cosmological model). Figures 1 displays appropriate fits to the observed data for $q_o = 0.5$. The solid curve is an appropriate fit to the data of Lanzetta et $al.$ (1995). The dashed curve displays a dust-corrected evolution of the Lanzetta et $al.$ (1995) data typical of that calculated by Pei and Fall (1995). Clearly, the effects of dust can have a dramatic impact on the inferred evolution of the neutral hydrogen. We will return to this effect later. For the time being we assume the observed evolution of $\Omega_{\mathrm{HI}}(z)$ approximates closely the true evolution. The dotted curve of figure 1 is an appropriate fit to the preliminary data of Storrie-Lombardi et $al.$ (1995), which suggests a lower value of Ω_{HI} at $z > 3$.

Defining Ω_i as $\Omega_g X_i$, where X_i is the gas mass fraction of element i, we can follow the evolution of the elemental abundances with z through the following equation

$$\begin{aligned}
\frac{d\Omega_i}{dz} = &\left[\int_{m(z)}^{3} m\Psi(z_m^f)\Phi(m)Y_i(z_m^f)dm\right.\\
&+ r\int_{m3(z)}^{16} m_b\left\{\int_{\mu_m}^{0.5} f(\mu)\Psi(z_m^f)Y_i(z_m^f)d\mu\right\}\Phi(m_b)dm_b\\
&\left.+ (1-r)\int_{m3(z)}^{16} m\Psi(z_m^f)\Phi(m)Y_i(z_m^f)dm + \int_{m16(z)}^{m_{up}} m\Psi(z_m^f)\Phi(m)Y_i(z_m^f)dm - \Psi(z)X_i\right]\frac{dt}{dz}
\end{aligned}\tag{7}$$

Here Y_i is the elemental stellar yield, written as the mass of element i in the ejecta divided by the initial mass of the star from which it was ejected. We have adopted the yield calculations of Renzini and Violi (1981) for low mass stars, of Woosley and Weaver (1995) for massive stars, and of Thielemann et $al.$ (1986) for type Ia supernovae. The parameter r parameterizes the contribution of the type Ia supernovae to the elemental evolution. Other than the rate of type Ia supernovae, the only observable reported here that this contribution significantly affects is the Fe abundance. We assume here a constant value $r = 1/200$, which provides agreement with the present extragalactic supernova rates (see later). The additional integral here is over the binary distribution function $f(\mu)$, where μ is the ratio of secondary mass to total binary mass m_b. We have adopted the distribution function of Greggio and Renzini (1983), $f(\mu) = 24\mu^2$. Note that the lower limits of integration $m3$ and $m16$ have the same meaning as before except that they have lower limits of 3 and $16M_\odot$, respectively. For most IMF's raising the upper limit of $m_{up} = 40M_\odot$ makes little difference to the results.

We now solve the above equations in order to determine the chemical evolution of the cosmic gas as a function of redshift.

2.1. Star Formation Rates

We wish to compare our results with those obtained previously using an IRA (Lanzetta et $al.$. 1995, Pei and Fall 1995). Many predicted properties of the evolving gas arise from the calculated SFR. So let us first investigate the SFR determined from the above relations and compare them with those determined assuming an

IRA. We determine an IRA solution by setting $\Psi(z_m^f) \to \Psi(z)$ and $m(z)$ to some constant mass (say $0.85 M_\odot$) in eq. (4), giving

$$\Psi_{IRA}(z) = \frac{1}{1-R} \frac{d\Omega_g}{dz} \frac{dz}{dt} \tag{8}$$

where the return fraction R is

$$R = \int_{0.85}^{m_{up}} (m - m_r) \Phi(m) dm \quad . \tag{9}$$

Figure 2 illustrates the results for three different assumed IMF's (using the solid curve of figure 1). The dashed curves correspond to the IRA approximation and solid curves to the real calculations. The calculations are for a Salpeter IMF ($x = 1.35$), and two extreme slopes of $x = 0.35$ and $x = 2.35$. This range of x should encompass all reasonable IMF's. It is seen that the IRA is a good approximation except at extremely flat IMF's. These trends are as expected since for flat IMF's relatively more matter is being ejected at high redshift.

2.2. Elemental Abundances

Next we calculate the elemental abundances as function of redshift. The form of the IMF in our calculations is the main effect which alters the absolute level of most predicted elemental abundances. We find that an IMF with $x = 1.7$ matches well the solar metallicity mass fraction $Z = 0.02$ at $z \sim 0$. The Salpeter IMF gives $Z \sim 0.03$ at $z \sim 0$. (note capital Z is used for metallicity and small z for redshift). If one wishes to normalize the calculations to solar type metallicities at low redshift then values of x which do not deviate far from 1.7 are required. Figure 3a shows the redshift evolution of Z, Si, Cr, Fe and Zn for an IMF slope of $x = 1.7$ and for $q_o = 0.5$. Also shown is the Zn abundance as inferred by Pettini *et al.* (1994) from the weighted average of 17 damped Lyα ZnII observations. A complete compilation of the presently available abundance data can be found in Timmes *et al.* (1995a). Here we focus on the Zn abundance since it is widely used as the metallicity tracer in damped Lyα systems. This is largely due to the fact that its depletion onto dust grains is anticipated to be small. On the other hand, Cr is anticipated to be highly depleted onto dust grains, and its abundance probes the nature of the dust rather than the metallicity (see Pettini *et al.* 1994 for further discussion).

The predicted evolution of the elemental abundances are in broad agreement with IRA calculations. However, the predicted Zn curve is significantly lower relative to a constant-yield IRA calculation for this element. This effect is a result of the metallicity dependence (i.e redshift) dependence of the Zn yields from the type II supernovae calculations. To illustrate this point, the dashed curve of figure 3a is calculated assuming a constant Y_{Zn} yield at all redshift. Although a mass dependence is still included here, the only yields utilized are from the solar-metallicity type II calculations of Woosley and Weaver's (1995) tabulations. It can be seen that the inclusion of metallicity dependent yields results in a lower predicted Zn abundance. As Zn is the principal metallicity tracer in damped Lyα clouds, this effect helps to alleviate the apparent contradiction of the cosmic G-Dwarf problem as discussed by Lanzetta *et al.* (1995). The basic point is that direct use of Zn as a metallicity tracer at high redshift, tends to underestimate the true total metallicity Z at that redshift (by factors ~ 3 to 7). The other elemental abundances shown are only modestly affected by the metallicity dependence of the stellar yields (at the level of $\sim 25\%$).

In their study of galactic chemical evolution, Timmes *et al.* (1995b) note a similar effect of the Zn yield dependence on metallicity with regard to the galactic Zn/Fe evolution with Fe. Their calculations are in general agreement with stellar observations of Zn in the galaxy. However, it should be noted that although the galactic Zn/Fe ratios have scatter at a level roughly consistent with the metallicity dependent yield, there is no obvious increasing trend of the observed Zn/Fe ratio with Fe/H (Sneden *et al.* 1991). At the present time, it is not clear what the source of this potential discrepancy could be. Perhaps it is a peculiarity of the chemical evolution of our own galaxy, perhaps some correction (such as non-LTE effects) is required for the inferred stellar abundances, or perhaps the calculated stellar yields for Zn require adjustment. Of course if the latter is correct, then the previous discussion is modified, and constant-yield IRA calculations may in fact be reliable for the cosmological Zn abundance.

To put the above discussion another way; if one reads from the available stellar Zn/Fe data that a Zn underabundance at high redshift equals the underabundance of any other metal, then the dashed curve of figure 3a is the more appropriate Zn curve to use. However, this must mean that the stellar yield tabulations for Zn in massive stars (the principal source of Zn) we have utilized here are in error. There are of course potential sources of error in the yield tabulations, such as mass loss (which we neglect for massive stars), nuclear physics,

and the kinetic energy of type-II supernovae (we have adopted here the high kinetic energy yields of Woosley and Weaver). Other more minor issues which relate to the stellar yields are the low mass cut-off of $11 M_\odot$ we adopt, and the fact that the distribution of elements making up the total Z will not correspond directly with the tabulations. Future theoretical and observational work should finally resolve the issue of the Zn evolution. At the present time we simply make the point that use of the current state-of-the-art stellar yields results in a lower Zn abundance in the cosmic gas, and apparently a better fit to the inferred abundance of Zn at $z \approx 2.2$.

For comparison, we show in figure 3b the evolution of the abundances using a Salpeter IMF. Here we can see the impact that a change in slope of the IMF can have on the predicted abundances. As mentioned above, we see how higher metallicities are predicted by the shallower slope. Note also the different shape of the Zn curve, which can be attributed to the higher metallicity at a given redshift and the consequent change in the stellar yields at that redshift. With regard to the discussion above, this implies that the accuracy of Zn as a metallicity tracer is also dependent on the IMF.

We also investigated the effects of using the dotted curve of figure 1. This curve approximates the data of Storrie-Lombardi *et al.* (1995), which indicates lower gas densities at high redshift. However, we find no large effect on the predicted abundances with the use of this different $\Omega_{\mathrm{HI}}(z)$ curve. For example, we find the abundances to be within ~ 0.4 dex of the abundances shown in figure 3a.

The calculations above were repeated for $q_o = 0$. The differences in the elemental abundances for this modified cosmology were also found to be quite small. At $z = 3$ they were roughly 0.3 dex lower than the $q_o = 0.5$ calculation, with differences slightly smaller (larger) than this at lower (higher) redshift. This leads us to the next topic.

2.3. *Testing Cosmology*

In principal, one can utilize the abundance history in the damped Lyα systems to probe cosmology. Indeed, recently Timmes *et al.* (1995a) have advocated such a program, by utilizing the galactic age-metallicity relation to scale galactic chemical evolution directly into redshift space. This assumes that the chemical evolution history of the galaxy is identical to that in all of the observed damped Lyα systems. We prefer to utilize calculations based on the observed evolution of the cosmic neutral gas as inferred from damped Lyα systems to address this issue.

One can test the cosmological model by looking at the abundance ratio of two elements, where one of the elements is produced mainly by type II supernovae (eg O), and the other is produced mainly by type Ia supernovae (eg Fe). Basically one is trying to use the abundances to test the relationship between time and redshift, where the "clock" utilized is the lifetime of type Ia precursors. Since these supernovae are dependent on the evolution of relatively low mass systems, enough time must have passed ($\sim 1 \mathrm{Gyr}$) before they can be produced in significant numbers. Once the number of type Ia's become significant the O/Fe ratio should start to decline. This idea has been advocated before by Hamann and Ferland (1993) in the context of the evolution of QSO broad line gas.

Here we use our calculations to investigate the possibilities of measuring q_o by measuring abundances in damped Lyα systems (the IRA model would be of no value in this regard). Figure 4 shows the O/Fe (by mass) as function of the redshift. The solid curve is for $q_o = 0.5$, and dashed curve is for $q_o = 0$. The effect of the cosmology on the abundance ratio is clearly seen here. It is unfortunate that the type Ia supernovae rate exhibits a smooth rise – a more abrupt turn-on of the type Ia's would result in a more distinctive drop in the O/Fe ratio. In order to use these curves as a test of q_o, accuracy in the abundance ratio to better than 30% will be required. It will therefore be a difficult experiment to determine q_o from future observations of the abundances in the damped Lyα systems. A similar conclusion is drawn regarding determination of the cosmological constant by this means. For comparison, the effect of varying the IMF on the O/Fe ratio is given (dotted curve). It can be seen that for a Salpeter IMF the effect is smaller than the variations induced by the cosmology.

2.4. *Dust Corrected Yields*

As mentioned earlier, the inferred redshift evolution of the neutral hydrogen can be dramatically influenced if observational bias introduced by dust contamination is a serious issue. The dashed curve of figure 1 is typical of the correction that may have to be applied to the observed (solid curve) $\Omega_{\mathrm{HI}}(z)$ evolution (Pei and Fall 1995). To show the potential effect of dust corrections on the elemental abundance evolution we utilize the dust-corrected curve of figure 1 to re-calculate the element evolution for $q_o = 0.5$. *If* this curve did in fact represent the true evolution of the cosmic gas, the evolution of the elemental abundances would be as shown in figure 5. When compared to the calculations of figure 3a it can be seen that the redshift evolution of the elements are significantly affected. These calculations can be compared directly with the closed-box IRA calculations of Pei and Fall (1995).

Again we find that the IRA determination of the abundance evolution is in broad agreement with the more exact treatment, except for the evolution of the Zn abundance. Here the predicted Zn abundance seems somewhat lower and does not provide as good a fit to the inferred abundance of Zn as the dust-free calculation.

Clearly the potential impact of dust-corrections on the chemical evolution of the cosmic gas can be very significant. There is then the danger that the ability to use observed abundances in damped Lyα systems as a probe of evolution in the early universe, can become seriously compromised. Not only could it be that a large fraction of the neutral gas is hidden, but that the true cosmic elemental abundances (obtained from a weighted average over all column densities) are also unmeasurable. This would render the confrontation of calculation with observation untenable. In view of this, we wish to turn to other possible future experiments which may shed some light on whether dust contamination is a source of significant observational bias.

3. TESTS OF DUST CONTAMINATION

One way of investigating possible dust contamination is to pose the question; what other observables are there of the evolution of the cool neutral gas at high redshift? In this section we will address this question by comparing calculations which utilize the the observed (solid) and dust-corrected (dashed) evolutionary curves of figure 1? Use of other observed or dust-corrected curves for the neutral hydrogen evolution will not be further studied. In this section we are only interested in possible signals of the dust effects, and the two curves of figure 1 we adopt provide good examples by which to carry out comparison tests. However, we do note that use of the dotted curve of figure 1 (and its similarly dust-corrected curve) would only modestly impact the results below. Also, unless otherwise stated we will adopt $x = 1.7$ since this IMF matches solar metallicities at low z, and we adopt the conventional wisdom that the universe is flat ($q_o = 0.5$). We will note circumstances where the proposed tests are significantly affected by relaxation of these two choices.

3.1. *Deuterium Evolution*

Deuterium is the best isotope to study in order to investigate dust effects. The reasons for this are the following. (a) We can assume deuterium is destroyed in stellar interiors and never present in any significant quantities in stellar ejecta – this makes our calculation independent of any stellar yield calculation. (b) Unless an unlikely combination of chemical evolution effects in individual absorption clouds conspire, a plateau in the deuterium abundance *vs.* redshift plot will indicate the primordial deuterium abundance. This will make the lack of an abundance determination in the dust-hidden clouds unimportant. (c) Assuming the validity of standard big bang nucleosynthesis, the primordial abundance of deuterium is known *a priori* to be confined within a narrow range. Although not as important as (a) and (b), this last point does allow for a consistency check.

Adopting point (a) above, and defining $\Omega_D = \Omega_g(z)X_D$, where X_D is the gas mass fraction of deuterium, the evolution of the deuterium abundance can be described by

$$\frac{d\Omega_D}{dz} = \frac{H_o^{-1}\Psi(z)X_D}{(1+z)[\Omega_m(1+z)^3 - \Omega_k(1+z)^2]^{1/2}} \quad .$$

(10)

The ratio of deuterium to its primordial value can then be calculated for the different curves of the neutral hydrogen evolution. The resultant evolution of the deuterium as a function of redshift can be seen in figure 6. It is clear that the dust-corrected evolution of deuterium is significantly different from that calculated using the observed $\Omega_{\mathrm{HI}}(z)$ curve. The presence of a longer plateau in the dust-corrected calculation arises from the later onset of significant star formation in this model. Calculations for different IMF's using the observed $\Omega_{\mathrm{HI}}(z)$ curve were also investigated. For example, the deuterium evolution for a Salpeter IMF (no dust correction) is also shown in figure 6. In addition, we note that IMF's with values of $x > 2$ result in little depletion of deuterium, and can mimic the dust-corrected calculation. Clearly then, the IMF can have an important impact on the deuterium evolution. With regard to probing dust contamination, it is therefore important that the actual IMF be tied down from other considerations such as the metallicity production associated with it. For example, IMF's with $x > 2$ result in very low metallicity at $z = 0$. Changes in the cosmology had smaller effects on the deuterium evolution than those imposed by dust effects.

One can see that in principal, future observations of deuterium in damped Lyα systems can be a probe for the presence of dust-induced observational bias. However, the accuracy required to distinguish between the observed and dust-corrected curves is $\sim 10\%$, thus making this test extremely difficult in practice. As an aside, it is interesting to note that the calculations predict the present cosmic deuterium abundance to be reduced by only $30 - 40\%$ from its primordial abundance. Figure 6 also indicates the redshift at which deuterium must be observed in order to probe its true primordial abundance.

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3.2. *Extragalactic Gamma-Rays*

The rate of type II supernovae, R_{II} (number/Gyr/unit comoving volume), can be determined through

$$R_{II} = \rho_c \int_{m16(z)}^{m_{up}} \Psi(z_m^f)\Phi(m)dm + (1-r)\rho_c \int_{m11(z)}^{m_{up}} \Psi(z_m^f)\Phi(m)dm \tag{11}$$

where the lower limits of integration $m16$ and $m11$ have seem meaning as before, and have lower limits of 16 and $11 M_\odot$, respectively. The rate of type Ia supernovae is given by

$$R_I = r\rho_c \int_{m3(z)}^{16} \Phi(m_b)\left\{ \int_{\mu_m}^{0.5} \Psi(z_m^f)f(\mu)d\mu \right\} dm_b \tag{12}$$

With $r = 1/200$, the ratio $(R_I/R_{II})_o$ is in agreement the observed extragalactic supernova rates (Vandenbergh 1991). In the context of the present study we believe this is the best way to normalize the type Ia contribution to the element evolution, rather than use of a solar abundance ratio like O/Fe. Given the large uncertainty in the extragalactic supernova rates, however, there is certainly room to alter the value of r slightly, thereby affecting the predicted Fe abundance.

The rate of type II supernovae is shown in figure 7 for the different evolutionary curves. It is evident that these rates peak at significantly different values of redshift. Due to the later star-formation in the dust-corrected calculation, the value of R_{II} peaks at the relatively lower redshift $z \sim 2$. This opens up the possibility of probing the importance of dust effects by scrutinizing the diffuse extragalactic gamma-ray background for the presence of spectral features.

Extragalactic gamma-rays can be produced through cosmic ray interaction processes such as $p + p \rightarrow \pi^o + \text{anything} \rightarrow 2\gamma$. A flux of gamma-rays produced in this fashion would have a negligible contribution below half the rest mass of the pion, 70 MeV. In principle, by assuming that the extragalactic cosmic ray flux is directly proportional R_{II}, adopting some efficiency for converting supernova kinetic energy into cosmic-ray energy (typically 1%), and knowing the gamma-ray emissivity per atom induced by cosmic rays (Dermer 1986), one could calculate the number of gamma-rays as a function of redshift. The absolute value arising from such a calculation would depend on the normalization of R_{II} at some redshift, and the shape and evolution of the cosmic-ray spectrum. However, the main point we wish to make here is that one would anticipate the gamma-ray flux produced by cosmic-ray interactions to peak at the redshift z_p corresponding to the peak of R_{II}. This being the case, a depression in the diffuse extragalactic gamma-ray background maximized at $70/(1+z_p)$ MeV should be present. The gamma-ray depression should be maximized at approximately 14 MeV if the observed $\Omega_{HI}(z)$ curve represents the true evolution, and 23 MeV if the dust-corrected $\Omega_{HI}(z)$ curve represents the true evolution of the cosmic gas. Note that in this case a change in the IMF does not alter the value of z_p, although it could alter the depth of any spectral feature (smaller IMF slopes providing larger effects). The dotted curve of figure 7, which corresponds to the observed evolution with a Salpeter IMF, illustrates this point.

The detectability of such a feature in the diffuse extragalactic gamma-ray background depends largely on the contribution of the cosmic-ray processes relative to the other sources of extragalactic gamma-rays (eg AGN). It is worth noting in this respect, that although cosmic-ray processes are thought to dominate the diffuse galactic gamma-ray background at $E > 200$ MeV, the anticipated 70 MeV spectral feature in the diffuse galactic gamma-ray background is likely dwarfed by brehmsstrahlung processes (Weber *et al.* 1980). However, based on galactic cosmic-ray production of beryllium, Silk and Schramm (1992) argue that up to 50% of the diffuse extragalactic gamma-ray background could arise from cosmic-ray processes, and that a $70/(1+z)$ MeV spectral feature could be detectable (we caution that this latter prediction is based on a galactic normalization of the Be abundance and therefore somewhat uncertain).

There is no evidence for a depression in the diffuse extragalactic gamma-ray background in the presently available data (Thompson and Fichtel 1982; Gehrels and Cheung 1995). Instrumentation on board the *GRO*, has a sensitivity to diffuse emission of $10^{-5} \text{cm}^{-2}\text{s}^{-1}$ and an energy resolution of $\sim 10\%$. This means that if no spectral feature is detected by GRO then it must be substantially below the 50% level. Nonetheless, given the above discussion, future scrutiny of the observed diffuse extragalactic gamma-ray background in the $10 - 70$ MeV range is warranted. With future increases in sensitivity it may be possible to probe the evolution of the neutral gas at high redshift by this means.

3.3. *MeV Neutrino Background*

Knowledge of the type II supernovae rate can also be used to calculate the energy density of the MeV neutrino background. This neutrino background arises from the convolved neutrino emission of all relic type II supernovae . In principal, this is a much "cleaner" signal of the peak in the type II supernovae rate compared to the gamma-ray background test, since the latter requires a series of assumptions regarding conversion of supernovae kinetic energy into cosmic ray energy. Of course, the difficulty lies in the detection of the relic MeV neutrino background. However, we note that this background is in fact a target of the Superkamiokande neutrino detector currently under construction in Japan.

One can show that the energy density of the MeV neutrino background is given by

$$\rho_\nu = \frac{F_E}{H_o} \int_0^{z_c} \frac{n(z)dz}{(1+z)^5 [\Omega_m(1+z)^3 - \Omega_k(1+z)^2]^{1/2}} \tag{13}$$

where F_E is the energy per unit time emitted in neutrinos by a type II supernova, and $n(z)$ is the number density of type II's. Coupling the supernova rates shown in figure 7 with eq.(13), we calculate that the mean energy of the MeV neutrino background assuming R_{II} as determined from the observed $\Omega_{\rm HI}(z)$ evolution is ~ 10 times that calculated assuming a constant comoving number density $n(z) = n_o(1+z)^3$, where n_o is the present type II rate (for the constant rate we assume a cutoff at $z_c = 7$). For R_{II} as determined from the dust-corrected $\Omega_{\rm HI}(z)$ evolution, we find the mean energy to be ~ 7 times that calculated with the constant rate. (Note that due to the different supernova rates at low z in figure 7, the constant rate backgrounds are different for the two curves.) With $z_c = \infty$ one finds the MeV neutrino background calculated using the dust corrected $\Omega_{\rm HI}(z)$ evolution is ~ 1.6 that calculated using the observed $\Omega_{\rm HI}(z)$ evolution. Indeed, this is the main point that we wish to make here. Detailed calculations of the MeV neutrino background determined directly from the inferred evolution of the neutral gas at high redshift, provides the possibility of probing dust contamination effects. The actual size of the change in energy density will of course depend on the assumed dust contamination.

We should caution that use of the MeV neutrino background as outlined above requires accurate knowledge of the IMF and the cosmological model parameters. For example, use of a Salpeter IMF (see dotted curve of figure 7) results in a factor 2.7 increase in the neutrino energy density compared to the $x = 1.7$ calculation. Also, the above calculations adopted $q_o = 0.5$. For comparison, calculations with $q_o = 0$ show the neutrino energy density to be lowered by a factor of ~ 3. The implies that only if the IMF and cosmology are known can the MeV neutrino background be used as a probe of dust. Alternatively of course, one can be turn this argument around. That is, assuming a reliable inference of the $\Omega_{\rm HI}(z)$ evolution and IMF, this technique can be used as a measurement of q_o.

Due to these effects it may be worth exploring in greater detail the connection between neutrino astronomy and observations of damped Lyα systems. Assuming a reliable normalization of the calculations, and the convolution of the inferred $\Omega_{\rm HI}(z)$ evolution with the neutrino energy spectra emitted by type II supernovae, one could determine absolute values of the relic neutrino flux anticipated from a given cosmological model. Further discussion and other uses of the MeV neutrino background can be found in Bisnovatyi-Kogan and Seidov (1984); Krauss *et al.* (1984); Woosley *et al.* 1986; Totani *et al.* (1995). This latter paper also discusses in detail the expected detection rate of the MeV background by Superkamiokande, which is is typically a few events per year. Actual use of this test will likely require next generation neutrino detectors.

3.4. *Modified Dust Correction*

Finally, we wish to conclude our calculations with a brief note regarding the possible magnitude of dust obscuration. In probing the possible effects of dust obscuration, Pei and Fall (1995) assumed a constant dust-to-gas ratio for all column densities at a given redshift – a reasonable approximation given the aims of their study. However, it is very unlikely that all clouds at a given redshift possess the same metallicity, and therefore considerations of a non-constant dust-to-gas ratio at a given redshift are of interest. Here we expand on the analysis of Pei and Fall to further investigate this.

For illustration, consider the closed-box IRA result which implies that U the ratio of the column density N to the initial unevolved column density N_u evolves like $U = \exp(-Z/y)$. Here y is the *net* yield (see Tinsley 1980). Now assuming that the metallicity is proportional to the dust-to-gas ratio k, i.e. $Z = ak$ where a is some constant, one can show that if each N has a *unique* value of k then a straightforward extension of Fall and Pei's (1993) analysis applies. The "true" and observed functions $f(N,z)$ (see eq. 1) are related through

$$f_t(N,z) = f_o(N,z) \exp\left[-\beta \frac{y}{a} \ln U \frac{N_u}{10^{21}{\rm cm}^{-2}} \zeta\left(\frac{\lambda_B}{1+z}\right) \exp(-ak/y)\right] \quad . \tag{14}$$

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Here β is related to the exponent of the observed luminosity function of quasars, and $\zeta(\lambda)$ is the ratio of the extinction at a wavelength λ relative to that in the B band. Adopting $\beta = 2$ and $\zeta = (\lambda/\lambda_B)^{-1}$, figure 8 shows how the dust-correction can be substantially reduced by this particular dependence of k on N (dotted curve). We have illustrated this effect by assuming for *all* clouds $N_u = 10^{22} \text{cm}^{-2}$, and have normalized to $Z = 0.002$ and $k = 0.05$ at $U = 0.1$. The solid curve of figure 8 is that corresponding to the observed distribution at $z = 2.5$, and the dashed curve shows the dust correction applied to f_o assuming a constant $k = 0.05$ (which is typical of the k expected at $z = 2.5$). Although the effect of the dust in this new calculation is largely dependent on the normalization conditions, the point remains that for a reasonable choice of parameters the impact of dust effects can be significantly reduced relative to a calculation assuming a constant dust-to-gas ratio. For the calculation illustrated here the dashed curve of figure 8 gives an $\Omega_g(z = 2.5)$ value of roughly 1.4 times that determined using the dotted curve.

The calculation completed here is overly simplistic in that all the damped Lyα systems commenced evolution at some high redshift with the same column density, and that subsequent evolution of the column density is attributed only to star formation. Of course, the initial spectrum of the cloud column densities will be determined by some underlying theory of structure formation, and therefore in a more realistic calculation one would not expect a *unique* value of k for each value of N. However, even at a given N a dispersion in the range of k will have little effect on our conclusion; that a trend in which larger values of N have lower values of k leads to a smaller correction to the observed $\Omega_{\text{HI}}(z)$ curves. Indeed, the main point we wish to make here, is that a relaxation of the constant k approximation can lead to significantly reduced dust obscuration effects, and that a relaxation of this approximation is entirely reasonable.

4. DISCUSSION AND CONCLUSIONS

Studies of chemical evolution are normally plagued by the many-parameter facet of the calculations, and there are many factors which can influence of the details of the calculations reported here. Uncertainty in the IMF, stellar yields, stellar lifetimes, and stellar mass loss, can all play a role in influencing the predicted abundances. We have further explored this parameter space within what we regard to be a reasonable ranges of uncertainties. The changes we find in the predicted abundances are roughly as expected. For example, changes of factor two in the stellar yields results in roughly factor two changes in the predicted abundances. Our basic conclusions regarding the chemical evolution of the elements are not seriously affected by reasonable variations of the above parameters.

Another potential source of error, is the insistence that the present metallicity from our calculations approximates the solar metallicity. In doing so we have assumed that the weighted average of the metallicity in *all* galaxies at the present epoch will give roughly the solar value. Although there is some evidence to support such a view, one must remember that this is a substantial assumption. It is normalization to $Z \sim 0.02$ at small redshift that determined the slope of the IMF in most of our calculations. We do not believe that normalization at $z = 0$ to the solar abundance of some minor element is a safe procedure, and have avoided doing so in the calculations reported here.

Invalidation of the closed-box assumption we have adopted here could result in significant changes to our conclusions. For most circumstances the presence of inflow of unprocessed material would increase the elemental abundances at a given redshift. An outflow of processed material will have a smaller effect. For the probes of dust contamination, the length (in z space) of the deuterium plateau could be strongly influenced by inflow. Also, since in principle the z dependence of any inflow/outflow would be unknown, one could think of circumstances in which the peak of the supernova rates were moved to new values of z_p, thereby affecting our discussions of the gamma-ray and MeV neutrino backgrounds. The assumption of a closed box model is therefore important to our proposed tests of dust contamination.

In summary, assuming a closed box model we have explored the chemical evolution of the cool neutral gas in the early universe using the redshift evolution of this gas as inferred from observations of damped Lyα systems. Our principal results are:- (i) Assuming the accuracy of the stellar yields employed here, the abundance of the main metallicity tracer of such systems, Zn, is significantly affected by the constant yield assumption. Direct integration of the chemical evolution equations with redshift dependent yields are recommended for this important element. (ii) Use of the O/Fe ratio can be used to probe cosmology, although the accuracy required by future observations will make this a difficult experiment. (iii) Other possible signals of the importance of dust obscuration could be evident in the deuterium redshift evolution, the extragalactic gamma-ray background, and the MeV neutrino background. Searching for these signals will also require very high sensitivity. (iv) Correlations of column density with metallicity can substantially reduce the importance of dust related effects.

The next few years should see an ever increasing wealth of data on the evolution of the neutral gas and elemental abundances in the damped Lyα systems. Eventually this data should be able to tightly constrain the parameters which influence the cosmic chemical evolution of neutral gas, such as the IMF and the contribution of observational bias due to dust. This new data combined with further theoretical study should provide an exciting tool for probing the evolution of galaxies in early universe.

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Figure 1. Possible evolution histories of $h\Omega_{\mathrm{HI}}$ as a function of redshift ($H_o = h100$ km s^{-1} Mpc^{-1}). The solid curve is a good match to the recent data of Lanzetta *et al.* (1995); the dashed curve is a dust-corrected representation of the solid curve; and the dotted curve matches the recent data of Storrie-Lombardi *et al.* (1995) ($q_o = 0.5$ assumed).

Figure 2. Star formation rates as a function of redshift in units of Ω_g per Gyr ($q_o = 0.5$ assumed).

Figure 3a. Redshift evolution of the elemental mass fractions (shown as log) for an IMF slope $x = 1.7$ ($q_o = 0.5$ assumed).

Figure 3b. Redshift evolution of elemental mass fractions (shown as log) for an IMF slope $x = 1.35$ ($q_o = 0.5$ assumed).

Figure 4. Redshift evolution of the O/Fe ratio (by mass) for different cosmologies and IMF's.

Figure 5. Redshift evolution of elemental mass fractions (shown as log) for an IMF slope $x = 1.7$ and dust correction included. ($q_o = 0.5$ assumed).

Figure 6. Redshift evolution of the ratio of the deuterium abundance to its primordial abundance ($q_o = 0.5$ assumed).

Figure 7. Type II supernova rates shown here as R_{II}/ρ_c. (R_{II} in units Gyr^{-1} per unit comoving volume).

Figure 8. Effects of dust on $f(N, z)$ for constant and variable gas-to-dust ratios.

APPENDIX

For reference, the numerical output of the mass fractions for our calculations assuming the solid curve of figure 1, $q_o = 0.5$, and IMF slope of $x = 1.7$, is shown in table 1.

TABLE 1.
Element Mass Fractions (-log)

z	C	N	O	Mg	Si	Ca	Cr	Fe	Zn
5.0	4.8	5.3	3.9	5.3	4.9	6.1	6.7	4.9	8.2
4.5	4.6	4.9	3.7	5.0	4.6	5.8	6.5	4.7	7.9
4.0	4.3	4.6	3.4	4.8	4.4	5.6	6.2	4.4	7.7
3.5	4.1	4.3	3.2	4.6	4.2	5.4	6.0	4.2	7.5
3.0	3.8	4.1	3.1	4.4	4.0	5.2	5.8	4.0	7.3
2.5	3.6	3.9	2.9	4.2	3.8	5.0	5.6	3.7	7.1
2.0	3.3	3.7	2.7	4.1	3.7	4.8	5.4	3.5	6.9
1.5	3.1	3.5	2.6	3.9	3.5	4.7	5.2	3.3	6.7
1.0	3.0	3.4	2.5	3.8	3.4	4.5	5.0	3.0	6.5
0.5	2.9	3.3	2.4	3.6	3.2	4.3	4.8	2.8	6.3